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# The numerical radius of a weighted shift operator

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## Abstract

This article briefly resumes previous works of the author, joint with Professor Hiroshi Nakazato, on the  $q$ -numerical radius of a weighted shift operator with geometric weights and periodic weights.

## 1. Introduction

Let  $T$  be a bounded linear operator on a complex Hilbert space  $H$ . For  $0 \leq q \leq 1$ , the  $q$ -numerical range  $W_q(T)$  of  $T$

$$W_q(T) = \{\langle T\xi, \eta \rangle : \|\xi\| = \|\eta\| = 1, \langle \xi, \eta \rangle = q\}.$$

$W_q(T)$  is a bounded convex subset of  $\mathbf{C}$ (cf. [12]). Its  $q$ -numerical radius

$$w_q(T) = \sup\{|z| : z \in W_q(T)\}.$$

When  $q = 1$ ,  $W_q(T)$  reduces to the classical numerical range of  $T$  which is defined by

$$W(T) = W_1(T) = \{\langle T\xi, \xi \rangle : \|\xi\| = 1\}.$$

Consider a weighted shift operator in infinite matrix form

$$T = \begin{bmatrix} 0 & 0 & 0 & 0 & \cdots \\ s_1 & 0 & 0 & 0 & \cdots \\ 0 & s_2 & 0 & 0 & \cdots \\ 0 & 0 & s_3 & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix},$$

where the weights  $\{s_n : n = 1, 2, 3, \dots\}$  is a bounded sequence. Define a unitary operator

$$U = \text{diag}(c_1, c_1 c_2, c_1 c_2 c_3, \dots),$$

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$c_1 = 1$ ,  $c_{n+1} = \overline{s_n}/|s_n|$  if  $s_n \neq 0$ , and  $c_{n+1} = 1$  if  $s_n = 0$ . Then

$$UTU^* = |T|.$$

Hence, we may assume the weights of a weighted shift operator are nonnegative when the  $q$ -numerical range is involved.

Let  $T$  be a weighted shift operator with weights  $\{s_n\}$ . Shields [7] showed that  $W(T)$  is a circular disk about the origin. Further, if the weights are periodic, Ridge [6] proved  $W(T)$  is closed if any of weights is zero, and Stout [9] showed  $W(T)$  is an open disk if all weights are nonzero. In particular, if  $s_n = 1$ , for all  $n$ , it is well known that  $W(T)$  is the open unit disk and  $w(T) = 1$ . Tam [10] proved  $W_q(T)$  is the closed unit disk for all  $0 \leq q < 1$ . It is interesting to ask what is the radius of the circular disk of  $W_q(T)$ ? Berger-Stampfli [1] gave a partial answer showing that for weighted shift operator with weights  $\{1+h, 1, 1, \dots\}$ ,  $1+h > \sqrt{2}$ ,

$$w(T) = \frac{1}{2} \left( ((1+h)^2 - 1)^{\frac{1}{2}} + ((1+h)^2 - 1)^{-\frac{1}{2}} \right).$$

In this paper, we examine the  $q$ -numerical radius of a weighted shift operator when its weights are in geometric sequence and periodic sequence.

## 2. Geometric weights

Let  $T$  be a linear operator, and  $T = UP$  be its the polar decomposition. The Aluthge transformation of  $T$  is defined by

$$\Delta(T) = P^{\frac{1}{2}}UP^{\frac{1}{2}}.$$

Suppose  $T$  is a weighted shift operator with geometric weights  $s_n = r^{n-1}$ ,  $0 < r < 1$ . Then  $P = \text{diag}(1, r, r^2, r^3, \dots, r^{n-1}, \dots)$ . and

$$\Delta(T) = \sqrt{r} T.$$

Applying Yamazaki inequality [13],

$$w(T) \leq \|T\|/2 + w(\Delta(T))/2,$$

we obtain a bound for the numerical radius.

**Theorem 2.1** (cf.[2]) Let  $T$  be a weighted shift operator with geometric weights  $\{r^{n-1}, n \in \mathbf{N}\}$ ,  $0 < r < 1$ . Then  $W(T)$  is a closed disk about the origin, and  $w(T) \leq 1/(2 - \sqrt{r})$

Let  $T$  be a weighted shift operator with finite square sum. Denote  $F_T(z)$  the determinant of  $I - z(T + T^*)$  given by

$$F_T(z) = 1 + \sum_{n=1}^{\infty} (-1)^n c_n z^{2n},$$

where

$$c_n = \sum s_{i_1}^2 s_{i_2}^2 \cdots s_{i_n}^2,$$

the sum is taken over

$$i_2 - i_1 \geq 2, i_3 - i_2 \geq 2, \dots, i_n - i_{n-1} \geq 2.$$

Stout [9] proved that  $w(T) = 1/(2\lambda)$ , where  $\lambda$  is the minimum positive root of  $F_T(z)$ . We present explicitly the series  $F_T(z)$  if  $T$  is a weighted shift operator with geometric weights.

**Theorem 2.2** (cf.[2]) Let  $T$  be a weighted shift operator with geometric weights  $\{r^{n-1}, n \in \mathbf{N}\}$ ,  $0 < r < 1$ . Then

$$F_T(z) = 1 + \sum_{n=1}^{\infty} \frac{(-1)^n r^{2n(n-1)}}{(1-r^2)(1-r^4)(1-r^6) \cdots (1-r^{2n})} z^{2n}.$$

For instance, if  $r = 0.2$ ,  $s_n = (0.2)^{n-1}$ , then by Theorem 2.1,  $w(T) \leq 1/(2 - \sqrt{r}) \approx 0.644$ . While from Theorem 2.2, the minimum positive root of  $F_T(z)$  is estimated by 0.980552, and thus  $w(T) \approx 1/(2 \times 0.980552) = 0.50991$ .

Substituting  $z = ir$  into  $F_T(z)$  in Theorem 2.2,

$$\begin{aligned} F_T(z) &= 1 + \sum_{n=1}^{\infty} \frac{(-1)^n r^{2n(n-1)}}{(1-r^2)(1-r^4)(1-r^6) \cdots (1-r^{2n})} z^{2n}, \\ F_T(ir) &= 1 + \sum_{n=1}^{\infty} \frac{r^{2n^2}}{(1-r^2)(1-r^4) \cdots (1-r^{2n})}. \\ 1 + \sum_{n=1}^{\infty} \frac{r^{n^2}}{(1-r)(1-r^2) \cdots (1-r^n)} &= \prod_{n=0}^{\infty} \frac{1}{(1-r^{5n+1})(1-r^{5n+4})} \quad (1) \end{aligned}$$

Sloane-Robinson [8] mentioned that the coefficients of the power series in the right-hand side of (1) are in expansion of permanent of the infinite tridiagonal matrix

$$\begin{bmatrix} 1 & 1 & 0 & 0 & \cdots \\ r & 1 & 1 & 0 & \cdots \\ 0 & r^2 & 1 & 1 & \cdots \\ 0 & 0 & r^3 & 1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}.$$

We consider a finite matrix of size  $n$ ,

$$A(n, r) = \begin{bmatrix} 0 & 1 & 0 & 0 & \cdots & 0 \\ r & 0 & 1 & 0 & \cdots & 0 \\ 0 & r^2 & 0 & 1 & \cdots & 0 \\ 0 & 0 & r^3 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & 1 \\ 0 & \cdots & \cdots & 0 & r^{n-1} & 0 \end{bmatrix}.$$

We are able to describe the numerical ranges of these tridiagonal matrices.

**Theorem 2.3** (cf.[3]) For  $n \geq m \geq 3$  and any real number  $r$ ,  $W(A(n, r)) \supset W(A(m, r))$ .

**Theorem 2.4** (cf.[3]) Let  $n = 2\ell - 1 \geq 5$ . Then  $W(A(n, -1))$  is the convex hull of the two ellipses

$$\{(x, y) \in \mathbf{R}^2, x^2 \pm 2 \cos(2\pi/(n+1))xy + y^2 = \sin^2(2\pi/(n+1))\}.$$

When  $n = \infty$ . We define the operator

$$A(\infty, -1) = \begin{bmatrix} 0 & 1 & 0 & 0 & \dots \\ (-1) & 0 & 1 & 0 & \dots \\ 0 & (-1)^2 & 0 & 1 & \dots \\ 0 & 0 & (-1)^3 & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}.$$

The numerical range of this operator has a special type of shape.

**Theorem 2.5** (cf.[3]) For

$$W(A(\infty, -1)) = \{z \in \mathbf{C} : -1 \leq \Re(z) \leq 1, -1 \leq \Im(z) \leq 1\} \setminus \{1+i, 1-i, -1+i, -1-i\}.$$

### 3. Periodic weights

Let  $T$  be a weighted shift operator with periodic weights

$\{s_1, s_2, \dots, s_m, s_1, s_2, \dots, s_m, \dots\}$ . Consider the  $m \times m$  weighted cyclic matrix  $S$  with weights  $\{s_1, s_2, \dots, s_m\}$

$$S = S(s_1, s_2, \dots, s_m) = \begin{bmatrix} 0 & 0 & 0 & \dots & 0 & s_m \\ s_1 & 0 & 0 & \dots & 0 & 0 \\ 0 & s_2 & 0 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & s_{m-1} & 0 \end{bmatrix}. \quad (2)$$

Numerical ranges of weighted cyclic matrices (2) have been developed by several authors, for examples, [4, 11].

**Theorem 3.1** (cf.[11]) Let  $S(s_1, s_2, \dots, s_m)$  be a weighted cyclic matrix defined in (2). Then

- (i)  $S(s_1, s_2, \dots, s_m)$  is normal if and only if  $|s_1| = |s_2| = \dots = |s_m|$ , which is also equivalent to  $W(S(s_1, s_2, \dots, s_m))$  is a regular  $m$ -polygonal region centered at the origin and the distance from the center to its vertices equal to  $|s_1 \dots s_m|^{1/m}$ .
- (ii)  $\partial W(S(s_1, s_2, \dots, s_m))$  contains a line segment if and only if the  $s_j$  are nonzero and the numerical ranges of the  $(m-1)$ -by- $(m-1)$  submatrices of  $S$  are all equal.

The  $q$ -numerical radius of a weighted shift operator with periodic weights is exactly the  $q$ -numerical radius of the corresponding weighted cyclic matrix.

**Theorem 3.2** (cf.[4]) Let  $T$  be a weighted shift operator with periodic weights  $\{s_1, s_2, \dots, s_m\}$  and  $S$  be the  $m \times m$  weighted cyclic matrix with weights  $\{s_1, s_2, \dots, s_m\}$ . Then  $w_q(T) = w_q(S)$  for every  $0 \leq q \leq 1$ .

Notice that the case  $q = 1$  of Theorem 3.2 is proved by Ridge [6]. We are capable of presenting the closed form of the  $q$ -numerical radius of a weighted shift operator with 2-periodic weights.

**Theorem 3.3** (cf.[4]) Let  $T$  be a weighted shift operator with periodic weights  $\{s_1, s_2\}$ . Then

$$w_q(T) = \frac{s_1 + s_2}{2} + \sqrt{1 - q^2} \frac{|s_1 - s_2|}{2}.$$

Let  $T$  be a weighted shift operator with periodic weights  $\{s_1, s_2, \dots, s_m\}$ . Denote  $w_q(T) = w_q([s_1, s_2, \dots, s_m])$ . We have the following fundamental results of  $q$ -numerical radii.

**Theorem 3.4** (cf.[4])

- (a)  $w_q([s_1, s_2, \dots, s_m]) = w_q(|s_1|, |s_2|, \dots, |s_m|)$ .
- (b)  $w_q([cs_1, cs_2, \dots, cs_m]) = |c|w_q([s_1, s_2, \dots, s_m])$ .
- (c) If  $0 \leq s_j \leq s'_j, j = 1, 2, \dots, m$ , then  $w_q([s_1, s_2, \dots, s_m]) \leq w_q([s'_1, s'_2, \dots, s'_m])$ .
- (d)  $w_q([1, 1, \dots, 1]) = w_q([1]) = 1$ .
- (e)  $\min\{|s_1|, \dots, |s_m|\} \leq w_q([s_1, \dots, s_m]) \leq \max\{|s_1|, \dots, |s_m|\}$ .
- (f)  $w_q([s_m, s_{m-1}, \dots, s_2, s_1]) = w_q([s_1, s_2, \dots, s_{m-1}, s_m])$ .
- (g)  $w_q([s_2, \dots, s_m, s_1]) = w_q([s_1, s_2, \dots, s_m])$ .

The  $q$ -numerical radii may change while the order of the weights are changed.

**Theorem 3.5**(cf.[4]) Let  $T$  be a weighted shift operators with 4-periodic. Suppose that  $s_4 \geq s_3 \geq s_2 \geq s_1 \geq 0$ . Then

$$w_q([s_2, s_4, s_3, s_1]) \geq w_q([s_1, s_4, s_3, s_2]) \geq w_q([s_1, s_4, s_2, s_3])$$

for  $0 \leq q \leq 1$ .

## 4. Perturbations

In this section, we perturb the  $q$ -numerical radius of a weighted shift operator with periodic weights.

**Theorem 4.1** (cf.[5]) Let  $T$  be a weighted shift operator with periodic nonnegative weights  $\{s_1, s_2, s_3, s_4, \dots, s_m\}$ ,  $m \geq 5$ , such that  $s_3 > \max\{s_1, s_2, s_4, \dots, s_m\}$ . Then the perturbation of the  $q$ -numerical radius is

$$w_q(T) = s_3 - \frac{(s_3^2 - s_2^2)(s_3^2 - s_4^2)}{2s_3(2s_3^2 - s_2^2 - s_4^2)}q^2 + c_3^{(4)}q^4 + O(q^5),$$

where  $c_3^{(4)} = c_3^{(4)}(s_1, s_2, s_3, s_4, s_5)$ .

Let  $T$  be a weighted shift operator with 4-periodic. we are able to find the perturbed coefficients up to the 4th degree.

**Theorem 4.2** (cf.[5]) Let  $T$  be a weighted shift operator with periodic non-negative weights  $\{s_1, s_2, s_3, s_4\}$  such that

$$s_3 > \max\{s_1, s_2, s_4\}.$$

Then the perturbation of the  $q$ -numerical radius is

$$w_q(T) = s_3 - \frac{(s_3^2 - s_2^2)(s_3^2 - s_4^2)}{2s_3(2s_3^2 - s_2^2 - s_4^2)}q^2 + c_3^{(4)}q^4 + O(q^5),$$

where

$$\begin{aligned} c_3^{(4)} &= -\frac{1}{8\tilde{\alpha}} + \frac{\tilde{\beta}}{16\tilde{\alpha}^4} - \frac{s_3}{8}, \\ \tilde{\alpha} &= -\frac{s_3(2s_3^2 - s_2^2 - s_4^2)}{2(s_3^4 - s_2^2s_4^2)}, \quad \tilde{\beta} = \frac{\beta_2}{\beta_1}, \\ \beta_2 &= 8s_3^3\left(\frac{s_2^2}{(s_3^2 - s_2^2)} + \frac{s_3^2}{(s_3^2 - s_4^2)}\right)^4, \\ \beta_1 &= -\left(\frac{s_2^2}{s_3^2 - s_2^2} + \frac{s_3^2}{s_3^2 - s_4^2}\right)^2 - 2\left(\frac{s_2^2}{s_3^2 - s_2^2} + \frac{s_3^2}{s_3^2 - s_4^2}\right)^3 \\ &\quad - \left(\frac{s_2^2}{s_3^2 - s_2^2} + \frac{s_3^2}{s_3^2 - s_4^2}\right)^4 + 4s_3^2\left(-\frac{s_2^4}{(s_3^2 - s_2^2)^3}\right. \\ &\quad \left. + \frac{2s_1s_2s_3s_4}{(s_3^2 - s_1^2)(s_3^2 - s_2^2)(s_3^2 - s_4^2)} + \frac{s_2^2}{(s_3^2 - s_2^2)^2}\left(\frac{s_1^2}{s_3^2 - s_1^2}\right.\right. \\ &\quad \left.\left. - \frac{s_3^2(2s_3^2 - s_2^2 - s_4^2)}{(s_3^2 - s_4^2)^2}\right) + \frac{s_3^2}{(s_3^2 - s_4^2)^3}\left(-s_3^2 + \frac{s_4^2(s_3^2 - s_4^2)}{s_3^2 - s_1^2}\right)\right). \end{aligned}$$

For 3-periodic weighted shift operator, we obtain the following perturbation.

**Theorem 4.3** (cf.[5]) Let  $T$  be a weighted shift operator with periodic non-negative weights  $\{s_1, s_2, s_3\}$  such that  $s_3 > \max\{s_1, s_2\}$ . Then, for sufficiently small  $q$ , the perturbation of the  $q$ -numerical radius is

$$\begin{aligned} w_q(T) &= s_3 - \frac{(s_3^2 - s_1^2)(s_3^2 - s_2^2)}{2s_3(2s_3^2 - s_1^2 - s_2^2)}q^2 + \frac{s_1s_2(s_3^2 - s_1^2)^2(s_3^2 - s_2^2)^2}{s_3^3(2s_3^2 - s_1^2 - s_2^2)^3}q^3 \\ &\quad - \frac{\gamma(s_3^2 - s_1^2)^2(s_3^2 - s_2^2)^2}{8s_3^5(2s_3^2 - s_1^2 - s_2^2)^5}q^4 + O(q^5), \end{aligned}$$

where

$$\begin{aligned} \gamma = & 16s_3^{12} - 32(s_1^2 + s_2^2)s_3^{10} + (30s_1^4 + 72s_1^2s_2^2 + 30s_2^2)s_3^8 \\ & - (11s_1^6 + 93s_1^4s_2^2 + 93s_1^2s_2^4 + 11s_2^6)s_3^6 + (s_1^8 + 34s_1^6s_2^2 + 162s_1^4s_2^4 \\ & + 34s_1^2s_2^6 + s_2^8)s_3^4 + (3s_1^8s_2^2 - 75s_1^6s_2^4 - 75s_1^4s_2^6 + 3s_1^2s_2^8)s_3^2 + 36s_1^6s_2^6. \end{aligned}$$

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